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Analysis of the photovoltaic solar energy capacity of residential rooftops in Andalusia (Spain)

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ABSTRACT

Fossil fuel energy resources are becoming increasingly scarce. Given the negative environmental impacts (e.g. greenhouse gas emissions) that accompany their use, it is hardly surprising that the development of renewable energies has become a major priority in the world today. Andalusia, with a mean solar radiation of 4.75 kWh/m^2 per day and a surface area of 87,597 km^2, is the region in Europe with the highest solar energy potential. This research study determined the solar energy potential in Andalusia for grid-connected photovoltaic systems installed on residential rooftops. A methodology was developed for this purpose, which first involved a description of building characteristics, followed by the calculation of the useful roof surface area where photovoltaic arrays could be installed. In the next phase of the study, the mean solar irradiation characteristics were defined as well as the technical parameters of the photovoltaic systems. All of these factors allowed us to estimate the amount of electricity that could be potentially generated per year by solar panels.

Contents

1. Introduction

The analysis of the current energy production model and its comparison with the evolution of energy consumption clearly reflect the limited nature of conventional energy resources as well as the progressive deterioration of the environment, stemming from this kind of energy model [1,2]. The dramatic increase in energy consumption in the European Union in recent years has brought with it a dependence on external energy sources that could reach 80% in 2020 if countermeasures are not rapidly taken. Fortunately, there is now a growing social awareness of the negative environmental impacts of fossil fuel energy as well as the environmental problems related to the use of nuclear energy. This new social conscience of environmental problems and possible solutions will have a direct effect on how energy challenges are met in the future. This will doubtlessly signify a reduction in fossil fuel energy consumption as well as an increase in the production of renewable energies or energies generated from natural resources.

This new energy model should be based on energy sources that are sustainable from an environmental perspective and safe with little or no risk of accidents. Such sources should also be in large supply so as to ensure their long-term availability [3]. The

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increased use and advancement of renewable energies offer a viable solution for environmental problems caused by other energy sources [2]. For this reason, current European policies are focused on the development and use of renewable energy [6].

The residential sector, whose energy consumption in Europe is 30.2% of the total, is clearly in a position to initiate actions conducive to energy sustainability [3]. One possible solution, which is now an essential component of the energy policies of most countries, is the production of solar energy by means of building-integrated photovoltaic systems, connected to the grid [4,5].

The region of Andalusia is located in southern Spain, and has a total surface area of 87,597 km^2. With an average solar radiation of 4.75 kWh/m^2 per day [6,7], it is the region in Europe with the highest solar energy potential for the production of this type of renewable energy [8,9]. Furthermore, the large volume of residential building construction in recent years and the deficit of conventional energy sources justify any initiatives conducive to the construction of self-sustainable residential buildings that are capable of producing their own energy for illumination, HVAC, electrical appliances, etc. The installation of building-integrated photovoltaic systems is a viable option for the achievement of energy sustainability.

The objective of this research study was to calculate the energy capacity of grid-connected photovoltaic arrays that could be mounted on building roofs. For this purpose, we used statistical construction data as well as digital urban maps obtained from Google Earth™ to measure the useful roof surface area of a representative sample of buildings of the total population. Among the factors considered were: building type, orientation, roof tilt angle, location, shading, as well as other competing uses, such as air conditioning and heating installations, elevator shafts, roof terraces, or penthouses [10]. We were thus able to estimate the electrical energy potential by calculating the useful roof surface area of the buildings and by dimensioning the type of photovoltaic solar array to be mounted on the roofs. This study compares the technical potential of rooftop photovoltaic solar energy in Andalusia with the total energy consumption in the residential sector. The final section of the article presents the conclusions that can be derived from this study.

2. Context and justification

In recent years, an enormous effort has been made to develop models that explain how energy consumption is distributed in residential dwellings. Such models have analyzed this problem with a wide variety of different methods that range from econometric analyses to individual studies of residential building types, which were then extrapolated to the total set of buildings [11]. Moreover, many research studies have tried to estimate the solar energy potential in relation to the total roof surface area as well as the total surface area of the geographic area targeted in the study [4].

In this sense, Spain is in a position to play a key role in the implementation of renewable energy technology in Europe [6] due to its surface area, investments in large solar energy plants, and numerous research projects funded by public and private organisms. The objective of this research study was to calculate the solar energy potential of building rooftops, based on the dimensioning and design of photovoltaic arrays that could be mounted on these surfaces. For this purpose, we developed a model that was subsequently applied and validated in the geographic region of Andalusia (Spain).

3. Methodology

Our aim was to estimate the energy capacity of photovoltaic solar energy systems that could be installed on the rooftops of residential buildings in Andalusia. In order to achieve this research goal, we carried out the following actions (see Fig. 1):

- The building sector was described in terms of construction statistics published by the Spanish Ministry of Development. This analysis provided us with the gross roof surface area for each building type. This information was obtained for each of the eight provinces in the region of Andalusia.
- We selected a representative sample of buildings, and statistically analyzed their roof surface area. This allowed us to contrast the results of this sample with those obtained in the previous analysis.
- The geometric characteristics of three building types (i.e. detached and semi-detached houses, town houses and row houses, and high-rise buildings) were defined. This made it possible to obtain the useful roof surface where photovoltaic arrays could be installed.
- The photovoltaic solar array was then designed, and the energy generation potential was calculated for each of the eight provinces in Andalusia.

The following sections describe the research phases in which the building types were characterized and the rooftop surface area obtained.

3.1. Building characterization. Total roof surface area

The statistical data used for this study refers to 2000–2007, and was compiled by the Spanish Government, more specifically, the General Directorate of Economic Programming, a subsection of the Secretary of State for Infrastructure, which is part of the Ministry of Development. This information was obtained by means of a data-collection questionnaire, based on building licenses granted by city governments.

These data are collected on a monthly basis by the Ministry of Development for all of Spain. The "no response" answer in a certain number of questionnaires was dealt with by stratifying city governments, according to province. This was done by calculating the expansion coefficients, based on the population of the municipalities and the number of licenses granted. The formula used was the following:

$$C_{ij} = \frac{P_{ij}}{p_{ij}} \cdot \frac{L_{ij}}{l_{ij}}$$

where C_{ij} is the elevation coefficient of stratum i in province j. P_{ij} is the population of the municipalities of stratum i in province j. p_{ij} is the population of the municipalities of stratum i in province j, who have answered the questionnaire. L_{ij} is the number of licenses granted in stratum i of province j. l_{ij} is the number of licenses with a questionnaire of stratum i in province j.

This expansion coefficient used the first factor P_{ij}/p_{ij} to correct the *no response* answer and L_{ij}/l_{ij} to correct the non-completion or the questionnaire. The final results were obtained by adding the questionnaires of each stratum-province and multiplying this figure by the expansion coefficient. The size of the sample, namely, the minimum number of municipalities received from each stratum (n), depended on the total number of municipalities (N), the desired confidence level (K), the variability of the building licenses granted (s), and the absolute error assumed for these licenses (e). The formula used was the following:

$$n = \frac{N^2K^2S^2}{e^2 + NK^2S^2}$$

Our study targeted all buildings with a residential function. Buildings were classified in three categories: (1) detached and/or semi-detached houses; (2) town houses or row houses; (3) high-

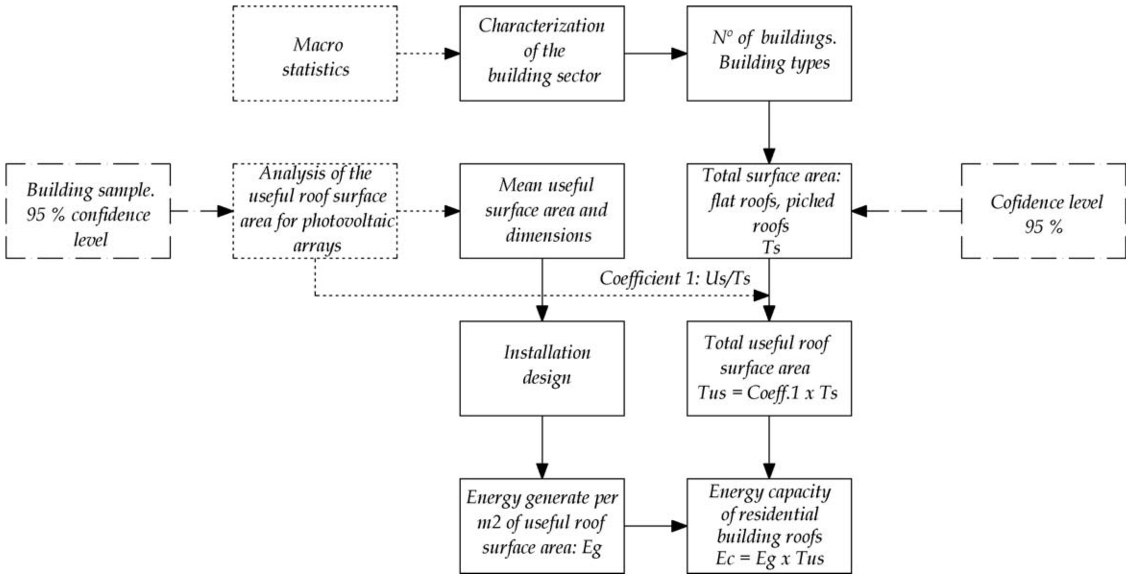


Fig. 1. Methodology.

rise apartment buildings. Based on statistical data collected for 2000–2007, we obtained the mean roof surface area for each building type (see example in Table 1).

The calculation of the number of buildings and their total roof surface area allowed us to obtain the mean roof surface area for each building type and each year studied. This operation was repeated for each year and building type in order to obtain the surface area for each province in Andalusia.

For the rest of the building types and years, we obtained the mean roof surface areas of each building type for new housing constructed in 2000–2007. These figures were used to estimate the roof surface area of the total number of buildings (Table 2).

Table 3 shows the data obtained for all of the provinces in Andalusia. It includes the mean roof surface area for each building type, which was used to obtain rooftop energy capacity. The total number of residential buildings in Andalusia is approximately 1,400,000. To obtain this information, we updated the housing census of 2001 by including information from the final building completion certificates, annually published by the Ministry of Development.

We extrapolated the characterization of the sample for 2000–2007 to the total population. This allowed us to obtain the number of buildings, according to building type (detached house, town house, or high-rise building) and roof type (flat or pitched).

Table 4 shows the roof surface area of the total number of residential buildings in Andalusia.

3.2. Useful roof surface area

The available roof surface area was obtained by selecting a representative sample of the population under study, namely the residential buildings in Andalusia. This was calculated from urban maps obtained from Google Earth™. These maps were exported and scaled with the AutoCAD® software application. This allowed us to obtain data, such as the roof surface area, the surface area of elements that could interfere with the photovoltaic system, the shaded area, and the surface occupied by other installations, such as HVAC, elevator shafts, antennas, etc. (Figs. 2 and 3).

The size of the sample was determined by random stratified sampling since the population under study had been previously divided into subpopulations (homogeneous strata for the characteristic being studied). An unrestricted random sample was independently selected for each stratum. An estimator was obtained for each stratum, which was calculated as an adequate

Table 1
Mean roof surface area for high-rise apartment buildings in 2007.

Building typology, 2007												
Province	No. buildings (Unit)				Total roof surface area (m^2)				Mean roof surface area/building (m^2/Unit)			
	0–2	3	4–5	6 or more	0–2	3	4–5	6 or more	0–2	3	4–5	6 or more
Almería	1,540	774	351	292	220,873.0	252,667.4	180,916.9	80,536.9	143.4	326.4	515.4	275.8
Cádiz	482	157	53	0	78,337.2	74,518.9	32,499.1	0.0	162.4	474.6	613.2	0.0
Córdoba	1,261	366	89	0	273,456.0	84,565.6	31,204.9	0.0	216.9	231.1	350.6	0.0
Granada	2,606	2,012	462	41	493,417.1	312,823.9	191,840.1	14,551.8	189.4	155.5	415.2	354.9
Huelva	979	145	65	22	259,241.0	41,873.2	29,982.0	14,213.1	264.8	288.8	461.3	646.1
Jaén	286	656	386	45	36,416.2	143,946.1	132,386.3	3,315.5	127.5	219.4	343.0	73.7
Málaga	1,468	1,047	347	92	201,822.7	385,129.4	204,186.3	47,791.4	137.5	367.8	588.4	519.5
Seville	1,730	641	78	47	225,315.7	98,788.6	26,239.0	43,623.3	130.3	154.1	336.4	928.2
Total	10,352	5,798	1,831	539	1,788,878.9	1,394,313.1	829,254.7	204,032.1	171.5	277.2	452.9	349.8
Total buildings (UD)				18,520	Total surface area (m^2)			4,216,478.7				

Table 2
Mean roof surface area, according to building type (province of Córdoba) in 2007.

Year	No. buildings (UD)				Mean roof surface area (m^2/building)		
	Detached houses	Town houses	High-rise buildings	Total	Detached houses	Town houses	High-rise buildings
2000	105	423	686	1,214	235.42	188.61	186.61
2001	140	559	738	1,437	210.74	173.48	181.56
2002	260	1,152	951	2,363	182.66	154.36	188.22
2003	265	755	1,206	2,226	209.99	198.87	197.51
2004	408	1,151	1,505	3,064	201.37	182.49	183.94
2005	499	993	1,725	3,217	221.62	204.89	175.40
2006	355	877	2,053	3,285	233.83	272.60	227.33
2007	195	581	1,716	2,492	370.22	257.67	226.84
			Weighted mean		*226.87*	*201.36*	*199.86*

Table 3
Characterization of the total number of residential buildings in Andalusia according to roof type.

Province	Total no. of buildings (UD)	Building types (UD)			Flat-roof buildings (UD)			Pitched roof buildings (UD)		
		Detached house	Town house	High-rise building	Detached house	Town house	High-rise building	Detached house	Town house	High-rise building
Almería	90,134	12,180	26,997	50,957	7,554	16,744	31,605	4,626	10,253	19,352
Cádiz	155,625	17,962	52,349	85,314	8,322	24,254	39,526	9,640	28,096	45,788
Córdoba	132,643	29,941	54,933	47,769	12,481	22,899	19,912	17,460	32,035	27,857
Granada	147,522	33,299	61,095	53,127	7,698	14,124	12,282	25,601	46,971	40,845
Huelva	100,765	8,982	44,525	47,258	3,240	16,061	17,047	5,742	28,464	30,211
Jaén	127,655	15,852	68,639	43,164	2,526	10,939	6,879	13,326	57,701	36,285
Málaga	286,532	64,329	89,363	132,841	18,794	26,108	38,810	45,535	63,255	94,030
Seville	357,996	55,271	159,095	143,631	30,284	87,172	78,699	24,986	71,923	64,932
Total	1,398,871	237,814	556,996	604,061	90,899	218,300	244,760	146,915	338,697	359,301

Table 4
Roof surface area of the total number of buildings in Andalusia.

Province	Total flat roof surface area (m^2)			Total pitched roof surface area (m^2)			Total (thousands of m^2)
	Detached house	Town house	High-rise building	Detached house	Town house	High-rise building	
Almería	1,563,352.41	3,095,629.80	7,542,885.95	957,257.63	1,895,487.68	4,618,590.84	19,673.20
Cádiz	2,100,249.63	4,178,612.16	8,963,327.45	2,432,965.67	4,840,576.94	10,383,274.28	32,899.01
Córdoba	2,831,505.55	4,610,890.91	3,979,771.24	3,961,158.62	6,450,444.81	5,567,534.61	27,401.31
Granada	1,481,976.63	2,209,545.57	2,357,910.11	4,928,473.86	7,348,083.18	7,841,485.53	26,167.47
Huelva	631,367.86	2,258,196.75	3,458,535.72	1,118,951.74	4,002,125.11	6,129,444.94	17,598.62
Jaén	443,449.89	1,683,831.08	1,131,443.70	2,339,157.46	8,882,054.35	5,968,261.68	20,448.20
Málaga	4,834,293.29	4,311,052.34	9,745,234.92	11,712,635.70	10,444,915.62	23,610,976.71	64,659.11
Seville	5,211,443.61	12,795,433.17	13,050,049.46	4,299,815.55	10,557,152.01	10,767,228.75	56,681.12
Total	19,097,638.89	35,143,191.77	50,229,158.54	31,750,416.22	54,420,839.70	74,886,797.32	265,528.04

weighting of the estimates. The stratified sampling technique used was proportionate allocation based on the fact that the size of each stratum of the sample was proportional to its size within the population [12].

$$n = \frac{\sum \frac{W_h{}^2 \times s_h^2}{w_h}}{V + \frac{1}{N} \times \sum W_h \times s_h^2}$$

where n is the size of the sample; N is the total number of units; W_h is the weighting of the stratum (N_h/N); w_h is the weight that stratum h has in the sample (n_h/n); n_h is the number of sample units for each stratum; V is the anticipated variance, based on the margin of error (d^2/t^2); d is the chosen margin of error ($\bar{y} - \bar{Y}$); t is the confidence coefficient (1.96 to the 95% confidence level for a normal distribution (0,1)); s_h^2 is the estimated variance of each stratum h ($1/(n_h - 1) \times \sum_{i=1}^{n_h} (y_{hi} - \bar{y}_h)^2$).

The margin of error in the sample was 10%. Since the true variance of the population of each stratum h was unknown, we selected a small sample from the population of each stratum, and called it the pilot sample. Subsequently, we estimated the population variance in each of these samples for each building type. Finally, we applied the formula to estimate the size of the sample, and multiplied the sample size by each W_h, thus obtaining the population size of each stratum (Table 5).

This analysis allowed us to verify the previous data. For example, in the case of detached and semi-detached houses in Andalusia, the mean roof surface at a confidence level of 95% occurred within interval $(\eta \pm 1.96 \cdot \sigma / \sqrt{(p-n)/(p-1)})$ and was 215.79 m^2. The mean value, calculated by the previously described statistical analysis, was found to be 210.33 m^2, which was also within this interval. The comparison of data obtained with these two methods confirmed their goodness of fit.

Once the reliability of the data was confirmed by the previously described graphs, we determined the mean percentage of the useful surface area after eliminating the area occupied by elements interfering with the photovoltaic array. Table 6 shows the coefficient values that represent the gross surface area necessary to install the photovoltaic solar system.

Figs. 2 and 3. Calculation of the useful roof surface area, free of obstacles and shading.Google Earth™.

Table 5
Sample size, according to stratum.

Typology	$N_h = n_h$	$W_h = w_h$	s_h^2	n
Detached and semi-detached houses	196,691	0.14	2,065.62	111
Town houses and row houses	476,889	0.34	561.32	269
High-rise buildings	725,291	0.52	38,692.27	409
N	1,398,871	1		789

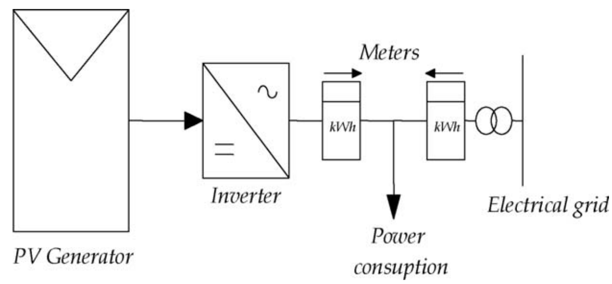


Fig. 4. Diagram of a grid-connected photovoltaic solar system.

3.3. Installation design

Fig. 8 shows the diagram of a roof-mounted photovoltaic system connected to the grid. It is composed of the following elements: (i) photovoltaic module; (ii) inverter/power conditioner; (iii) meters; (iv) connection to a conventional electrical grid (Fig. 4).

The expression used to estimate the energy (kWh/day) generated by the system is the following [13]:

$$E_p = G_{dm}(\alpha, \beta) \times P_{mp} \times \frac{PR}{G_{CEM}}$$

where $G_{dm}(\alpha,\beta)$ is the annual and monthly mean value of the daily irradiation on the solar generator in kWh/m^{2}día; P_{mp} is the peak generator power; G_{CEM} is 1 kWh/m^2; PR is the performance ratio.

To estimate the influence that the choice of photovoltaic panel can have on the final result, we calculated the energy for two installations with different types of panel. The photovoltaic panel chosen for the installation design was manufactured by ISOFOTON. This company has its factory in Andalusia and its production in MW was 4.5% of the total world market for photovoltaic cells in 2004.

3.3.1. Installation type 1

The first installation type was composed of *IS-170* photovoltaic modules manufactured by ISOFOTON, which had the following characteristics at standard test conditions:

- Dimensions: 790 ± 5 mm × 1600 ± 5 mm × 40 ± 2 mm.
- Maximum power rating: 170 W ± 3% W.
- Open circuit voltage: 44.4 V.
- TONC (800 W/m^2, 20 °C, AM 1.5, 1 m/s) 47 °C.

3.3.2. Installation type 2

The second installation type was composed of *IS-220* photovoltaic modules also manufactured by ISOFOTON, which had the following characteristics at standard test conditions:

- Dimensions: 1047 ± 5 mm × 1600 ± 5 mm × 40 ± 2 mm.
- Maximum power rating: 220 W ± 3% W.
- Open circuit voltage: 47.9 V.
- TONC (800 W/m^2, 20 °C, AM 1.5, 1 m/s) 47 °C.

Once the modules were defined, we obtained the elevations and layout of the photovoltaic array for the previously defined mean roof area surfaces. Our purpose was to determine the energy produced by the solar energy installation per unit of useful roof surface area (see Figs. 5–7).

The distance between photovoltaic modules were calculated by means of the following expression:

$$d = \frac{h}{\tan(61^\circ - \lambda)}$$

In the case of a flat roof, a perimeter space with a width of 1 m was considered necessary for maintenance work. We then calculated the number of solar panels that could be installed for

Table 6
Relation coefficient to obtain the useful roof surface area, free of obstacles.

	Detached and semi-detached houses		Town houses or row houses		High-rise buildings	
	Flat roof	Pitched roof	Flat roof	Pitched roof	Flat roof	Pitched roof
Coeff. Su/ST	0.740	0.974	0.796	0.983	0.654	0.789

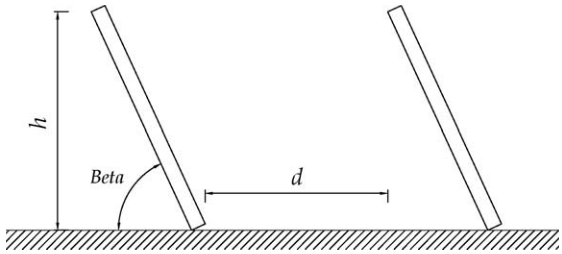


Fig. 5. Distance between solar panels.

the orientations shown in Fig. 6 (flat roofs) and Fig. 7 (pitched roofs).

For pitched roofs, our initial hypothesis was that the photovoltaic system would be installed on the roof façade receiving the largest amount of solar irradiation, and thus, the most energy. The array of solar panels would be attached to one of the roof sides. The mean roof tilt angle obtained from the analysis of a set of projects was found to be 16.708°. For the purpose of calculating the mean radiation, the S-E orientation was considered to be the most representative, and the solar panels would be mounted on the side of the roof that was most favorable to this orientation (see Fig. 8).

After obtaining the useful surface area for the location of photovoltaic arrays and defining the roof layout, we calculated the photovoltaic solar energy potentially generated.

To calculate losses from shading, the shadows produced by various construction elements (e.g. chimneys, elevator shafts, etc.) were studied by using the AutoCAD® software program (see Fig. 9).

The percentage of solar irradiation loss from shading was obtained by the representing the profile of the obstacle on the roof in the context of a band of the sun's trajectories during the year. As an example, Fig. 10 shows an elevator shaft located on the roof of a building.

The criterion followed in this study, which is based on the *Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red* [14] [Technical Specifications for Grid-Connected Installations] was to eliminate roof surfaces with a solar irradiation loss from shading greater than 10%.

4. Results

The roof surface area for all residential buildings in Andalusia was found to be 265.52 km^2: 104.47 for buildings with flat roofs

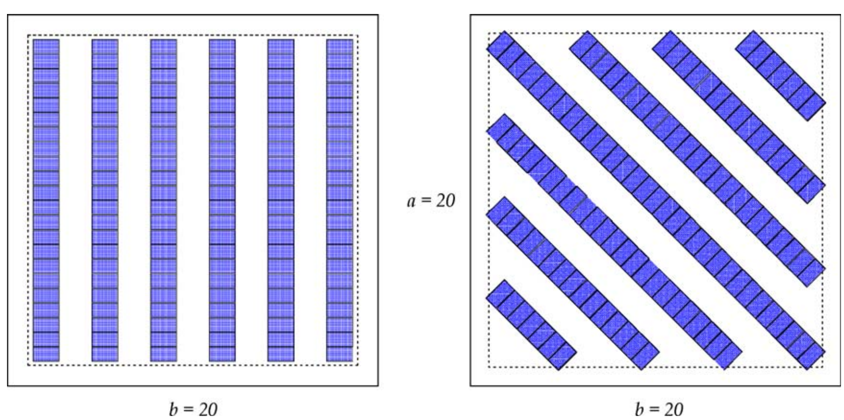


Fig. 6. Theoretical siting of the photovoltaic modules for two orientations. Flat roofs. IS-170 Modules

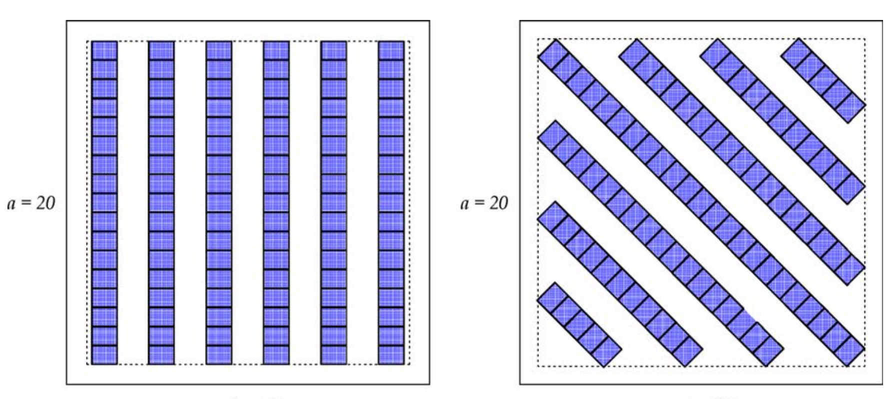


Fig. 7. Theoretical siting of photovoltaic modules for two orientations. Flat roofs. IS-220 Modules

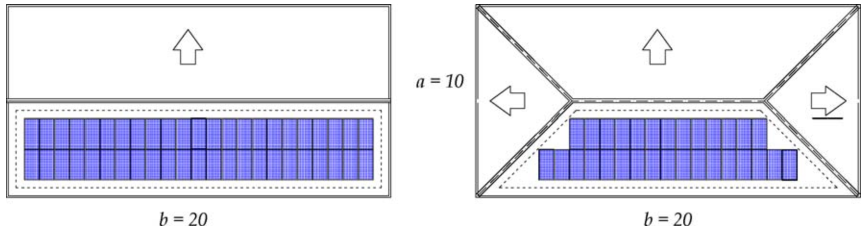


Fig. 8. Theoretical siting of IS-170 photovoltaic modules for two types of pitched roof.

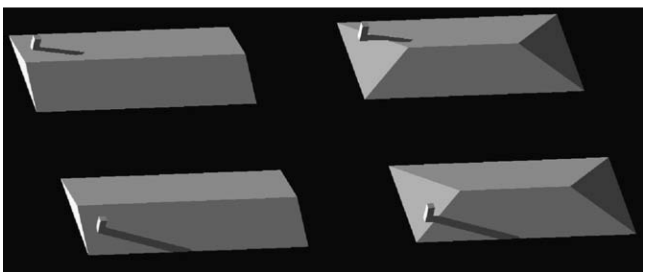


Fig. 9. Shadow projection for different days and times. Pitched roof and chimney.

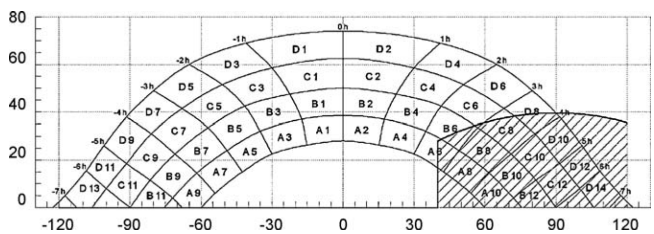


Fig. 10. Percentage of solar irradiation loss from shading for an elevator shaft located on a building roof: 17.47%.

and 161.05 km^2 for buildings with pitched roofs. The useful rooftop surface area, where a photovoltaic array could be mounted was 218.52 km^2, which comes to 82.29% of the total. The surface occupied by a photovoltaic array of IS-170 solar panels for each roof type is shown in Table 7.

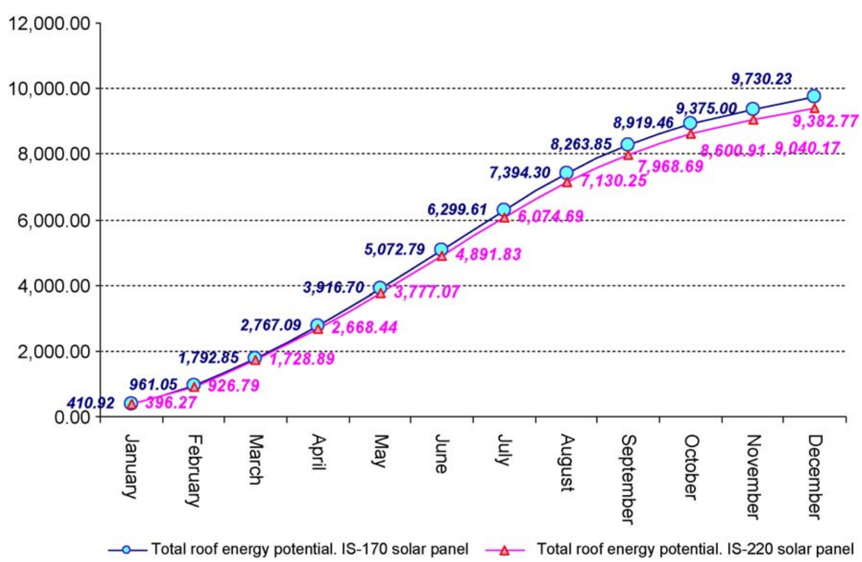
For a photovoltaic array of IS-220 solar panels, the occupation coefficient for flat roofs has the same value. For pitched roofs, the value is also very similar. For example, in the case of high-rise buildings, this value is 16.44% for flat roofs as compared to 16.83% for pitched roofs. The energy generation potential was estimated to be a total of 9.73 GWh for a photovoltaic array of IS-170 solar panels, and 9.38 GWh for an array of IS-220 solar panels (see Graph 1). The maximum photovoltaic potential for rooftop surfaces of residential buildings in Andalusia was thus calculated at 10.8 GWh/year.

The monthly distribution is represented on Graph 2.

The energy capacity for each roof type and m^2 of roof surface area for each province as well as the hypotheses of this research study are defined by the following ratios in Table 8.

The energy distribution for each Andalusian province is represented in Graph 3.

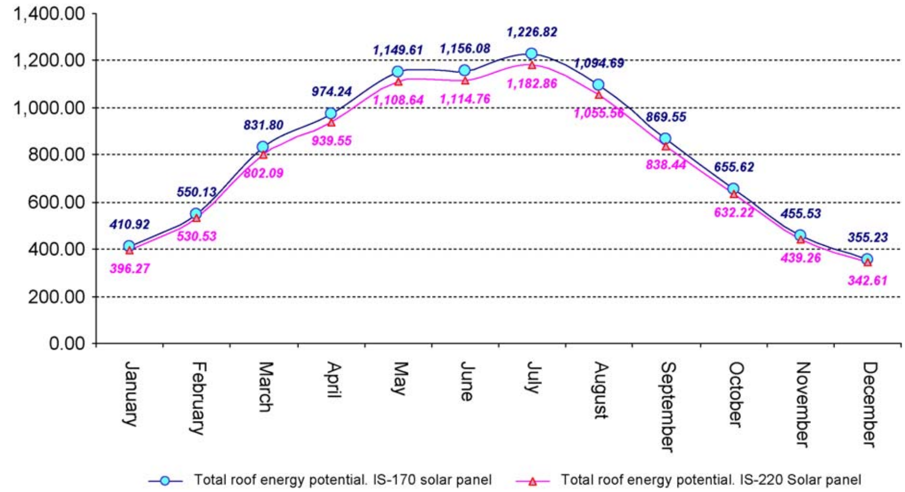
As previously mentioned, the total energy accumulated month by month during the year for the total number of buildings was



Graph 1. Total energy (GWh) generated by each solar panel type. Monthly accumulation.

Table 7
Percentage of roof surface area occupied by Installation type 2.

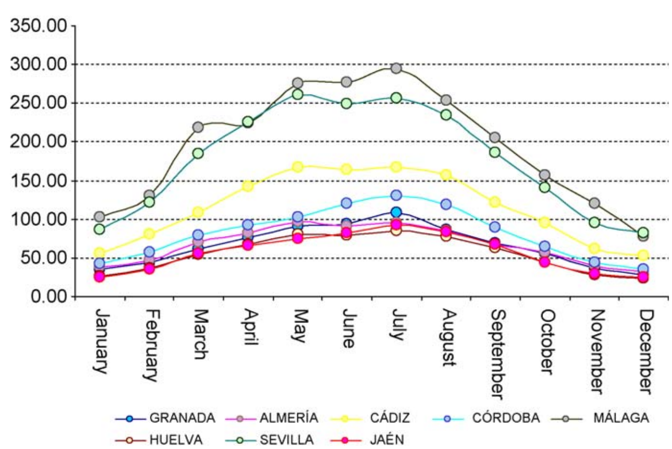
Flat roof			Pitched roof		
Detached houses	Town houses	High-rise buildings	Detached houses	Town houses	High-rise buildings
54.97%	53.72%	51.83%	21.12%	20.19%	16.83%



Graph 2. Total energy (GWh/month) generated monthly by each solar panel type.

Table 8
Ratios referring to the energy generation capacity per m^2 of rooftop surface area.

Province	Net coefficients		Gross coefficients	
	Flat roof (kWh/m^2 year)	Pitched roof (kWh/m^2 year)	Flat roof (kWh/m^2 year)	Pitched roof (kWh/m^2 year)
Almería	69.51	40.13	46.26	31.54
Cádiz	75.34	43.50	50.20	34.40
Córdoba	63.89	36.39	43.05	30.20
Granada	57.66	33.28	38.79	27.42
Huelva	70.53	40.71	47.02	32.39
Jaén	65.23	37.65	43.83	31.08
Málaga	68.78	39.71	46.08	32.01
Sevilla	64.48	37.22	43.26	30.38



Graph 3. Photovoltaic solar energy. Monthly production (GWh/month).

approximately 9.5 GWh/year. Of this amount, 5.0 GWh (51.5% of the total) could be generated by buildings with pitched roofs, and 4.5 GWh (48.5% of the total) could be generated by buildings with flat roofs.

5. Conclusions

In 2006, the energy consumption for uses related to the residential housing sector in Andalusia was 12,320 GW/year. The photovoltaic solar energy capacity for residential building rooftops in Andalusia if photovoltaic arrays were installed on all of them was calculated at 9.73 GW/year for a total roof surface of 265.52 km^2.

This would satisfy 78.89% of all energy needs, and would signify an external energy dependence of only 21.02%. Even this figure could be vastly improved if energy efficiency was increased and energy consumption was reduced. This seems to indicate that energy sustainability of residential dwellings in Andalusia is totally viable if the measures proposed in this study are taken.

This research clearly shows the importance of the design of roof-mounted elements when it comes to optimizing energy production.

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